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USE OF GEOSYNTHETICS FOR STABILIZING RECYCLED BALLAST IN RAILWAY TRACK SUBSTRUCTURES

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ABSTRACT

Traditional ballasted railway track substructure usually consists of graded layers of granular media of ballast and subballast (capping) placed above a compacted subgrade (formation soil). Ballast particles breakdown and deteriorate progressively under heavy train cyclic loading. Breakage of ballast is always associated with railway track deformation, which requires costly regular track maintenance in the form of replacing the degraded (recycled) ballast with fresh aggregates and subsequent re-compaction (tamping). In this paper, the use of geosynthetics for improving the deformation and degradation characteristics of recycled ballast is investigated. The prospective use of three different types of geosynthetics (i.e. geogrid, geotextile, and geocomposite) in enhancing the performance of recycled ballast under cyclic loading is examined using a large-scale prismoidal triaxial rig. A plane strain finite element analysis (PLAXIS) of the prismoidal triaxial rig is also carried out and used to obtain the optimum location of geosynthetics in railway track substructure. The results indicate that the use of geosynthetics for stabilizing the recycled ballast in railway tracks improves the performance characteristics of the track and consequently, reduces the track maintenance cost.

INTRODUCTION

The classical railway track is basically consisted of a flat framework of rails and sleepers, which are supported on a compacted bed of ballast and subballast (capping) that is laid on natural or improved subgrade (formation soil). Ballast supports the wheel loading imposed on the rails, and transmits this load to the subgrade at an acceptable level, while preventing excessive settlement. Subballast provides the effective drainage and filtration needed to protect the subgrade soil from softening and mud pumping. Ballast is generally derived from high quality igneous or metamorphic rocks, which are disintegrated into small angular particles of desired gradation. Despite the apparent strong and tough mechanical characteristic of ballast, its particles are still vulnerable to degradation under heavy cyclic train loads. The crushed fine particles migrate within the ballast bed and fill the voids between larger aggregates, hence decreasing the volume, porosity, and drainage characteristics of ballast. Moreover, the crushed fine particles form a thin layer surrounding larger aggregates, which increases the compressibility and decreases the shear strength of ballast. During heavy rainfalls and in the absence of a good quality subballast (filter) layer, saturated subgrade fines (silts and clays) are mixed with water to form a slurry, which pumps up into the ballast layer under cyclic train load. In saturated tracks, the fouling of ballast by degradation or clay pumping may cause localized undrained track failure and differential settlement, which requires regular costly track maintenance. In situations where the ballast bed is severely fouled and in order to keep the track in its desired level of stiffness (resiliency), bearing capacity and drainage, the ballast needs to be cleaned or replaced by fresh ballast. The routine replacement of fouled ballast during the past several years has produced huge stockpiles of waste ballast, which are now considered as an environmental hazard in Australia. These large stockpiles of contaminated ballast create disposal problem, following the current strict regulations of the Environment Protection Authority.

In an attempt to reduce the accumulation of discarded ballast and minimize its harmful effect on the environment by further quarrying fresh ballast, the waste ballast may be cleaned, sieved, and re-used (recycled) and put back on the track. However, since the angularity of recycled ballast is decreased by the degradation of sharp corners in the previous loading cycles, it is expected that recycled ballast will give higher settlement and lateral deformation, compared with relatively more angular fresh ballast. Consequently, if recycled ballast is to be used in track, its mechanical properties need to be improved to comply with the required stability and safety criteria stipulated by various railway authorities. In this paper, the deformation and degradation behavior of recycled ballast under field simulated cyclic loading is investigated in the laboratory. A large-scale prismoidal triaxial rig is used for this purpose. The potential of using three types of geosynthetics (i.e. geogrid, geotextile, and geocomposite) in stabilizing recycled ballast, and minimizing track settlement and particle degradation, is examined. In addition, a plane strain finite element analysis (PLAXIS 2004) is used to simulate the behavior of recycled ballast in the prismoidal triaxial rig. The finite element numerical model is then used to obtain the optimum location of geosynthetics in rail track substructure.

CHARACTERISTICS OF BALLAST TESTED

The fresh ballast tested in the current study is collected from Bombo quarry (NSW), which is a major source of ballast used by RailCorp of NSW. It represents sharp angular aggregates of crushed volcanic basalt (latite). The recycled ballast is collected from Chullora stockpile near Sydney. The waste ballast, which is removed from the deteriorated track during maintenance, is collected, cleaned, and sieved in a recycling plant. The physical examination indicates that about 90% of the recycled ballast comprised of semi-angular crushed rock fragments (degraded ballast), while the remaining 10% consisted of semi-rounded river gravels and other impurities (sleeper fragments, cemented materials, etc.). The parent rock of recycled ballast remains mostly the same as that of fresh ballast. A capping layer of sand-gravel mixture is also used beneath the ballast specimen in the laboratory model to act as a filter and separator between the ballast and subgrade. A thin layer of compacted clay is also used beneath the capping layer to represent the subgrade. The grain size distribution of fresh and recycled ballast used in this study is typical of that is currently adopted by RailCorp of NSW. The physical characteristic of ballast and capping material are shown in Table 1.

PROPERTIES OF GEOSYNTHETICS USED

Three types of geosynthetics are used in this study to stabilize recycled ballast in the laboratory model. These are: (a) geogrid; (b) woven geotextile; and (c) geocomposite, a combination of geogrid and non-woven geotextile bonded together. Different properties of these geosynthetics are described below.

Table 1 – Grain size characteristics of ballast and capping material used

Material	Particle shape	d_{max} (mm)	d_{min} (mm)	d_{10} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	C_u	C_c
Fresh ballast	Highly angular	63.0	19.0	24.0	30.0	35.0	38.0	1.6	1.0
Recycled ballast	Semi-angular	63.0	19.0	24.0	30.0	35.0	38.0	1.6	1.0
Capping	Angular to rounded	19.0	0.05	0.07	0.17	0.26	0.35	5.0	1.2

C_u = Coefficient of uniformity and C_c = Coefficient of curvature.

Geogrid

The geogrid used in this study is a bi-oriented geogrid that is made of polypropylene and manufactured by extrusion and biaxial orientation to enhance its tensile properties. It is generally used for soil stabilization and embankment reinforcement. This geogrid has high tensile strength, high elastic modulus, and strong resistance to construction damage and environmental exposure. With its large apertures (>25 mm), this geogrid provides strong mechanical interlock with coarse ballast grains. The physical and strength characteristics of the geogrid used are given in Table 2.

Table 2 – Physical and strength characteristics of geogrid used

Characteristics	Unit	Data
Material	–	Polypropylene
Mass	g/m^2	420
Aperture size (rectangular)	mm × mm	40 × 27
Tensile strength at 2% strain	kN/m	10.5
Tensile strength at 5% strain	kN/m	21.0
Peak tensile strength	kN/m	30.0

Woven geotextile

The type of geotextile used in this study is a high strength woven geotextile that has a tensile strength of about 80 kN/m. This woven geotextile has also a good particle retention capability due to its small pore sizes (<0.3 mm), while offering adequate permeability to rapidly dissipate the excess pore pressures (if generated) in the track. The physical and strength characteristics of the woven geotextile used are given in Table 3.

Table 3 – Physical and strength characteristics of woven geotextile used

Characteristics	Unit	Data
Material	–	Polypropylene
Mass	g/m^2	450
Pore size	μm	250
Tensile strength	KN/m	80
Flow rate	Liters/m^2/sec	32

***Geocomposite* (*geogrid + non-woven geotextile*)**

A geogrid-geotextile composite that is manufactured by bonding the geogrid to a non-woven geotextile is used in this study. Adding the non-woven geotextile to the geogrid enables this geocomposite to provide filtration and separation functions. Due to large apertures (> 25 mm, see Table 2), geogrid alone cannot provide these functions effectively. In a geocomposite, the geogrid gives a strong mechanical interlock with the ballast grains and produces reinforcement, whereas the non-woven geotextile provides filtration and separation, and allows partial in-plane drainage. The physical and mechanical characteristics of the geocomposite used are given in Table 4.

Table 4 – Physical and strength characteristics of geocomposite used

Characteristics	Unit	Data
Geogrid		
Material	–	Polypropylene
Mass	g/m^2	560
Aperture size (rectangular)	mm × mm	40 × 27
Geotextile		
Material	–	Polypropylene
Mass	g/m^2	140

LABORATORY EXPERIMENTAL PROGRAM

Ideally, the behavior of railway ballast should be investigated in the real track under actual operating conditions. However, such field tests are very expensive, time consuming, and disrupt traffic. Moreover, many variables, which affect the proper formulation of definitive ballast relationship, are often difficult to control in the field (Jeffs and Marich 1987). Therefore, laboratory experiments that can simulate field load and boundary conditions are usually carried out on ballast specimens. Several investigators have used large testing chambers with rigid and fully restrained walls to study ballast behavior under cyclic loading (e.g. Atalar *et al.* 2001; Raymond and Bathurst 1994). However, the lateral movement of ballast in real railway tracks is not fully restrained, particularly in the direction perpendicular to the rails (Indraratna *et al.* 2001). The confinement offered by fully restrained cell walls is, therefore, a major shortcoming in physical modeling of ballast in the laboratory. In the current study, a large-scale prismoidal triaxial rig that allows its vertical walls to freely move in the lateral directions under imposed loads is designed and built to simulate lateral deformation of ballast occurring in the real track. Description of the large-scale triaxial rig is given below.

Large-scale Prismoidal Triaxial Apparatus

The large-scale prismoidal triaxial rig used in this study can accommodate specimens of 800 mm long, 600 mm wide, and 600 mm high. Figure 1 shows the large-scale prismoidal triaxial rig used and a schematic representation of the triaxial apparatus including specimen set-up is shown in Figure 2. This is a true triaxial apparatus where three independent principal stress can be applied in three mutually orthogonal directions. A system of hinge and ball bearings enables the vertical walls to move laterally. Since each wall of the rig can move independently in the lateral directions, the ballast specimen is free to deform laterally under cyclic vertical load and lateral pressures. The lateral confinement offered by the shoulder and crib ballast in an actual track is not sufficient to restrain lateral movement of ballast, hence, the prismoidal rig with unrestrained sides provides an ideal facility for physical modeling of ballast under cyclic loading. Although the actual stress states may not be exactly simulated in the regions of lateral boundaries, this particular design of the chamber reasonably simulates realistic track boundary conditions.

Figure 1 – Large-scale prismoidal triaxial rig

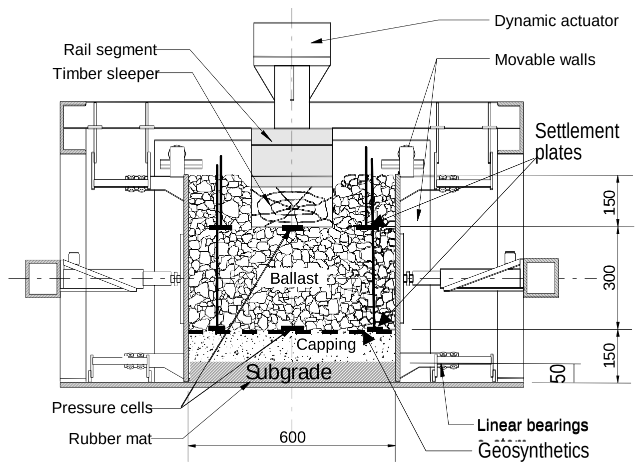


Figure 2 – Schematic representation of the large-scale triaxial rig (Indraratna and Salim 2003)

The cyclic vertical load (σ_1) is provided by a servo-hydraulic actuator and the load is transmitted to the ballast through a 100 mm diameter steel ram and a rail/sleeper arrangement (Figures 1 and 2). Intermediate and minor principal stresses (σ_2 and σ_3, respectively) are applied via hydraulic jacks, and are measured by attached load cells. Sleeper settlement and lateral deformations of the vertical walls are measured by 18 electronic potentiometers. Two pressure cells (150 mm × 150 mm × 22 mm each), one just beneath the sleeper and the other at the ballast/capping interface, are place inside the chamber to monitor ballast stress. The volume of these pressure cells are taken into account during computation of ballast density/void ratio. Eight settlement plates are installed at each of the sleeper/ballast and ballast/capping interfaces to measure vertical strain. To obtain high quality real time data, all load cells, pressure cells, and electronic potentiometers are connected to a data logger, and supported by a host computer. This fully instrumented equipment can measure all vertical and lateral loads and associated deformations.

Specimen Preparation

In order to simulate the track foundation in the laboratory, the prismoidal triaxial chamber was filled with subgrade and ballast materials in four layer. A compacted clay layer of 50 mm thick was placed at the bottom of the triaxial chamber to simulate the subgrade soil layer of a real track. Only a thin layer of clay was used in this laboratory model due to limited height of the triaxial chamber. Although no experimental investigation has been made within the scope of this study to examine the influence of subgrade thickness on ballast behavior, it is expected that a thicker subgrade of a specific thickness will equally affect the deformation and degradation response of various ballast specimens. Moreover, the vertical strains of ballast are computed by excluding the deformation of the capping and subgrade layers. In this respect, the thickness of clay layer used in the laboratory model is expected to have an insignificant influence on the test results, especially when comparing the response of different ballast specimens with and without geosynthetics inclusion. It is relevant to note here that subgrade vertical stresses are not measured during cyclic loading tests.

A capping layer (100 mm) of sand-gravel mixture was used above the clay layer to represent subballast of the track. A layer of compacted load bearing ballast (300 mm thick) was placed above the capping layer. An assembly of timber sleeper and rail section was placed above the compacted load bearing ballast, and the space between the sleeper and vertical walls was filled with crib ballast of 150 mm thick. One layer of geosynthetics (i.e. geogrid, woven geotextile, or geocomposite) was placed at the ballast/capping interface (i.e. the weakest interface) to improve the performance of recycled ballast. To completely recover the load bearing ballast after the test, two layers of thin geotextiles were placed above and below the ballast for isolation purpose only. A vibratory hammer was used to compact the ballast and capping layers. To achieve representative field density, compaction was carried out in several layers, each about 75 mm thick. A rubber pad of 5 mm thick was used beneath the vibrator to minimize particle breakage. Each test specimen was compacted to the same initial density. The bulk unit weights of the compacted ballast and capping layers were about 15.3 kN/m^3 and 21.3 kN/m^3, respectively, and the initial void ratio of ballast was 0.74. The number of cyclic triaxial tests carried out in this study was ten. These tests were conducted on fresh ballast, recycled ballast without geosynthetics, and recycled ballast with geosynthetics. To study the effect of saturation on recycled ballast, five tests were conducted on dry ballast and five were tested on wet ballast, with all specimens having identical loading and boundary conditions.

Test Procedure

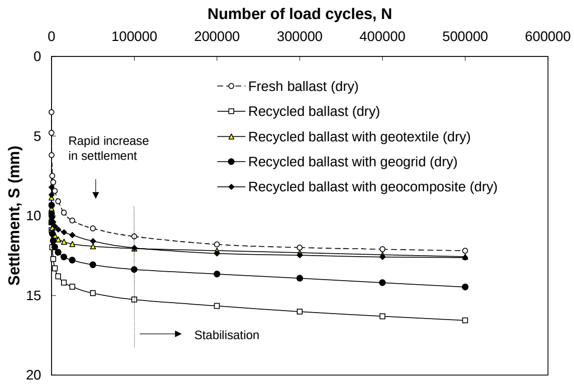
After preparing the test specimen, small lateral pressures (σ_2 = 10 kPa and σ_3 = 7 kPa) were applied to the triaxial specimens through hydraulic jacks to simulate field confinement. In a real track, the confinement is generally developed by the weight of crib and shoulder ballast, along with particle frictional interlock. An initial vertical load of 10 kN was applied to the specimens to stabilize the sleeper and ballast, and to serve as a reference for all settlement and lateral movements measured. At this stage of testing, initial readings of all load cells, pressure cells, potentiometers, and settlement plates were taken.

The cyclic vertical load was applied by a dynamic actuator with a maximum load of 73 kN to produce the same average contact stress at the sleeper-ballast interface for a typical 25 tons/axle traffic load. The cyclic load was applied at a frequency of 15 Hz, simulating a train speed of 80 km/hour for a distance of 1.5 m between two axles. The total number of load cycles applied was selected to be half a million, as previous test experience indicated that beyond this number of load cycles, the increase in settlement rate is negligible. The applied loading was halted at selected number of load cycles and the readings of settlement, wall movements, and loading magnitudes were recorded. For wet tests, the ballast specimens were gradually flooded with water before applying the cyclic load and water was added during cyclic loading to maintain 100% saturation. At the end of each test, the ballast specimens were sieved, and the change in particle size was recorded for the computation of particle breakage.

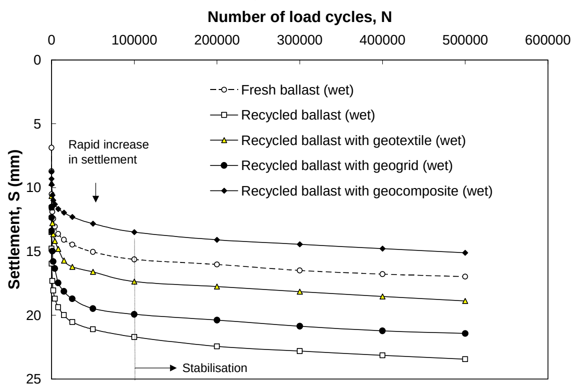
RESULTS AND DISCUSSION OF LABORATORY TESTS

The variation of total settlement of fresh and recycled ballast specimens against number of load cycles is shown in Figure 3 for samples with and without geosynthetics stabilization. The settlement of dry specimens is illustrated in Figure 3a, whereas the settlement of wet specimens is shown in Figure 3b. These figures confirm that the behavior of railway ballast under cyclic loading is highly non-linear. Similar behavior was also reported in the previous studies (Indraratna *et al.* 1998; Indraratna *et al.* 2000). As expected, fresh ballast produces the minimum settlement and recycled ballast without reinforcement shows much higher settlement compared to fresh ballast. It is believed that relatively higher angularity of fresh ballast contributes to better particle interlock, and therefore, less settlement. The breakage of sharp edges of recycled ballast, during previous loading cycles, is considered to be the key reason for its reduced friction, hence, higher settlement. Both fresh and recycled ballast show an increase in settlement, when saturated. The presence of water in saturated ballast acts as a lubricant, thereby reducing friction and increasing the settlement. Figure 3 clearly shows that inclusion of geosynthetics in recycled ballast improves its resistance to settlement and compares well with that of fresh ballast. The inclusion of geogrid in both dry and wet recycled ballast decreases the settlement moderately. In Figure 3b, it can be seen that the inclusion of woven geotextile in wet recycled ballast decreases the settlement significantly. The high strength woven geotextile provides reinforcement to recycled ballast, restricts particle movement at the ballast/capping interface, and at the same time prevents the migration of fines between the ballast and capping layer to a limited extent. These functions of the woven geotextile are the key reasons for increasing the stability of recycled ballast effectively. Figure 3a indicates that the settlement of dry recycled ballast decreases to that level of fresh ballast dry ballast, when a geocomposite is used. In saturated condition, Figure 3b shows that the inclusion of the geocomposite decreases the settlement of saturated recycled ballast to even less than that of saturated fresh ballast (without any geosynthetics). The geogrid of the geocomposite provides the mechanical interlock and arrests the lateral movement, while the non-woven geotextile prevents the ingress of fines from the capping and subgrade, thus, keeping the ballast relatively clean. The increased stability of recycled ballast provided by the inclusion of geocomposite demonstrates its potential as a reusable track material, and as a viable alternative for minimizing track construction and maintenance cost. It is also indicated in Figure

3 that all specimens show a rapid increase in settlement at the initial stages of cyclic loading, primarily due to void reduction (compaction).

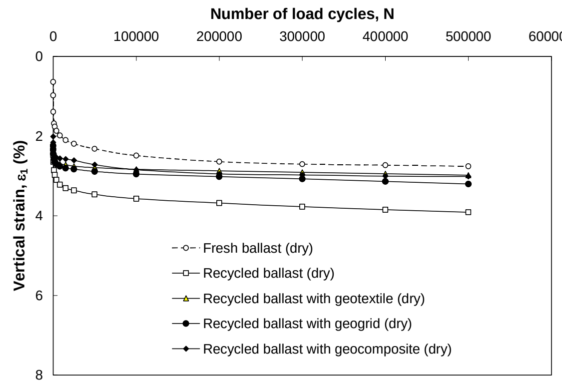


(a) Dry specimens

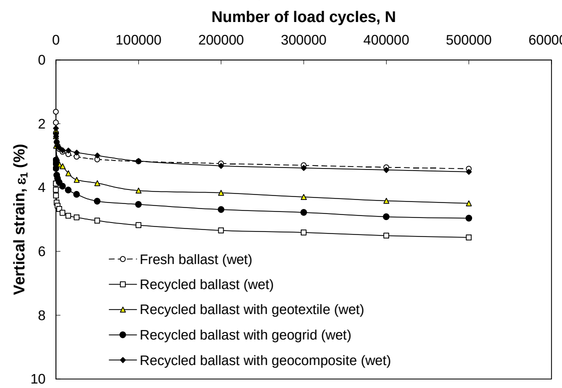


(b) Saturated specimens

Figure 3 – Variation of settlement (Indraratna and Salim 2005; Salim 2004)



(a) dry specimens

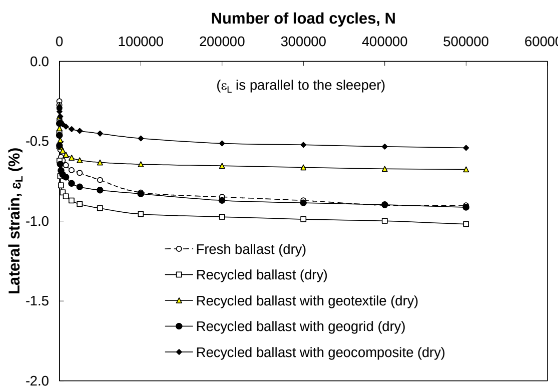


(b) Saturated specimens

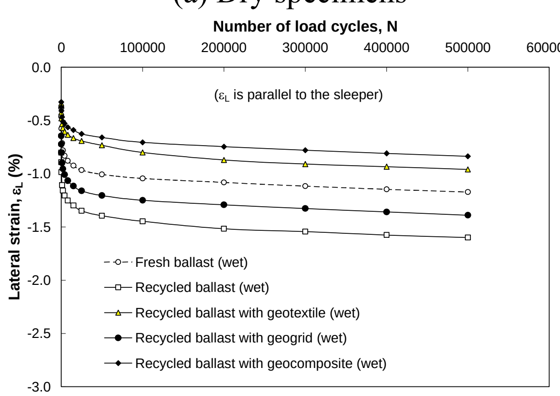
Figure 4 – Variation of vertical strain (Indraratna and Salim 2005; Salim 2004)

The sleeper settlement data and measurements of settlement plates placed at the ballast-capping interface were used to calculate the vertical strain (ε_l) of the ballast specimens. The lateral strains of ballast ε_L (the strain parallel to the sleeper) were calculated from the average lateral movements of the vertical walls and the initial lateral dimensions of the specimen. Figure 4 shows the vertical strain of ballast against the number of load cycles for saturated and dry test specimens. This figure verifies that the geocomposite is more effective, in reducing ε_l, than the geogrid or geotextile used alone. Figure 4 also indicates that after the initial rapid deformation, the vertical strain of ballast has a linear relationship with the number of load cycles, irrespective of the type of ballast and reinforcement. The variations of lateral strains ε_L with increasing number of load cycles are shown in Figure 5. The lateral strain of recycled ballast with no stabilization is higher than that of fresh ballast. Inclusion of geogrid in recycled ballast decreases the lateral strain slightly. However, inclusion of geotextile or geocomposite decreases ε_L to even less than that of fresh ballast at a higher number of load cycles. As observed in Figures 3-5, the deformation results for ballast specimens tested in dry condition are similar to saturated samples but indicating less settlement, vertical strains, and lateral strains.

The degradation of ballast under cyclic loading is measured in the laboratory by sieving each ballast specimen before and after the test, and recording the change in percentage retained on each sieve size ΔW_k. For this purpose, Marsal (1967) proposed the breakage index, B_g, which is defined as the sum of the positive values of ΔW_k. The variation of ΔW_k with different grain size of ballast are shown in Figure 6 and the breakage index values of different ballast specimens used in this study are given in Table 5. It is clear that fresh ballast indicates the least degradation, while recycled ballast is more vulnerable to breakage. In saturated condition, it experiences slightly higher degradation compared to dry ballast. The test results indicate that recycled ballast experiences 97% more breakage compared to fresh ballast under similar loading conditions. The presence of micro-cracks in recycled ballast under the previous loading cycles is believed to be a major reason for its higher particle degradation. In general, the results indicate that the inclusion of geosynthetics to recycled ballast decreases the degradation of recycled ballast significantly. Inclusion of a geocomposite layer in recycled ballast decreases particle breakage by about 48% (in dry condition) and 50% (in wet condition). According to the results given in Table 5, it is evident that recycled ballast stabilized with geocomposite (B_g = 1.60) is as good as fresh ballast (B_g = 1.63) in terms of breakage assessment. Figure 6 shows that the contributions of various geosynthetics used in decreasing the breakage of recycled ballast under cyclic loading are similar. It is also shown in Figure 6 that, irrespective of the type of ballast with or without geosynthetics, ballast particles of size 30 to 50 mm are the most vulnerable to degradation.

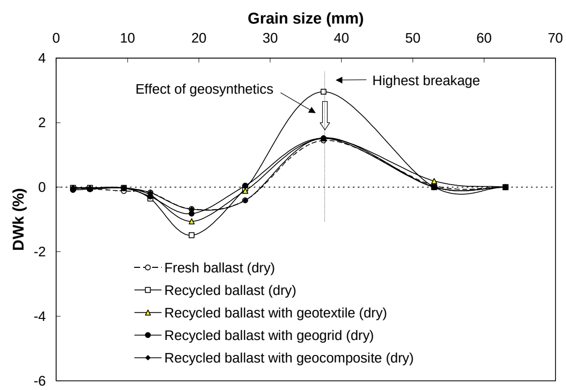


(a) Dry specimens

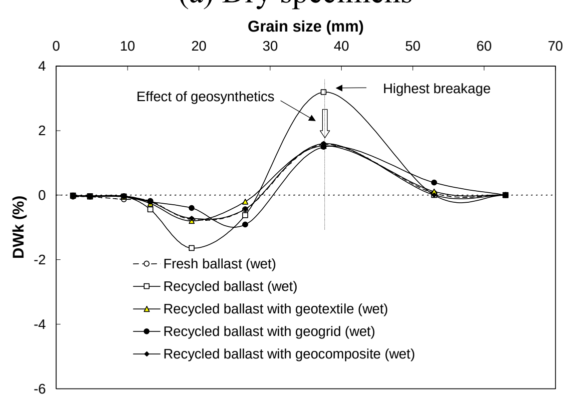


(b) Saturated specimens

Figure 5 – Variation of lateral strain (Indraratna and Salim 2005; Salim 2004)



(a) Dry specimens



(b) Saturated specimens

Figure 6 – Change in particle size (Indraratna and Salim 2005; Salim 2004)

Table 5 – Particle degradation of ballast

Type of test	Breakage Index, $B_g = \sum(\Delta Wk > 0)$	
	Sample in dry condition	Sample in wet condition
Fresh ballast	1.50	1.63
Recycled ballast	2.96	3.19
Recycled ballast with geogrid	1.70	1.88
Recycled ballast with geotextile	1.56	1.64
Recycled ballast with geocomposite	1.52	1.60

NUMERICAL MODELING BY FINITE ELEMENTS

In this part, the feasibility of using the finite element analysis (FEA) to simulate the behavior of ballast (wet fresh without geogrid and wet recycled with/without geogrid) in the prismoidal triaxial rig is investigated and used to obtain the optimum location of geosynthetics in rail track substructure. The results of the experimental work carried out on wet fresh and wet recycled ballast shown in Figure 3b are used to calibrate the finite element model. The large-scale prismoidal triaxial rig shown in Figures 1 and 2 is numerically simulated using the finite element code PLAXIS (2004). The finite element mesh used to simulate the track section in Figure 2 is discretized using 15 node plane strain triangular elements (Figure 7). Due to symmetry, only one half of the track section is considered in the numerical model. The material parameters and constitutive models used for each component of the track section are given in Table 6. Full details about the constitutive models used in Table 6 and their parameters can be found in PLAXIS manual (PLAXIS 2004). The train load is simulated by applying an equivalent uniformly distributed vertical dynamic load on the sleeper. This dynamic load has the same average contact stress at the sleeper-ballast interface for a typical 25 tons/axle traffic load with a frequency of 15 Hz that simulates a speed of 80 km/h. A total number of 100 load cycles are applied in the finite element analysis and their results are compared with the experimental data at the same number of load cycles. Applying more than 100 cycles in PLAXIS was not practically useful as PLAXIS behaves linearly elastic after this number of cycles. Lateral distributed static load is also applied to the movable steel walls of the prismoidal rig to simulate field confining pressure of 10 kPa. The damping effect is neglected in this study. The results of the finite element analysis are given in Table 7. It can be seen that good agreement is achieved between the finite element predictions and test results. This reveals that numerical modeling has the feasibility to simulate well the behavior of recycled ballast under cyclic loading. Table 7 also demonstrates that finite element analysis can simulate reasonably the effect of geosynthetics on the behavior of recycled ballast.

Inclusion of geosynthetics for improving the deformation characteristics of recycled ballast could be anywhere beneath the sleeper and within the ballast layer. However, to allow for tamping, geosynthetics must not be placed at a depth less than 150 mm below the sleeper. In this study, an attempt is carried out using the finite element analysis to obtain the optimum location of geosynthetics for improving the deformation characteristics of recycled ballast. The placement

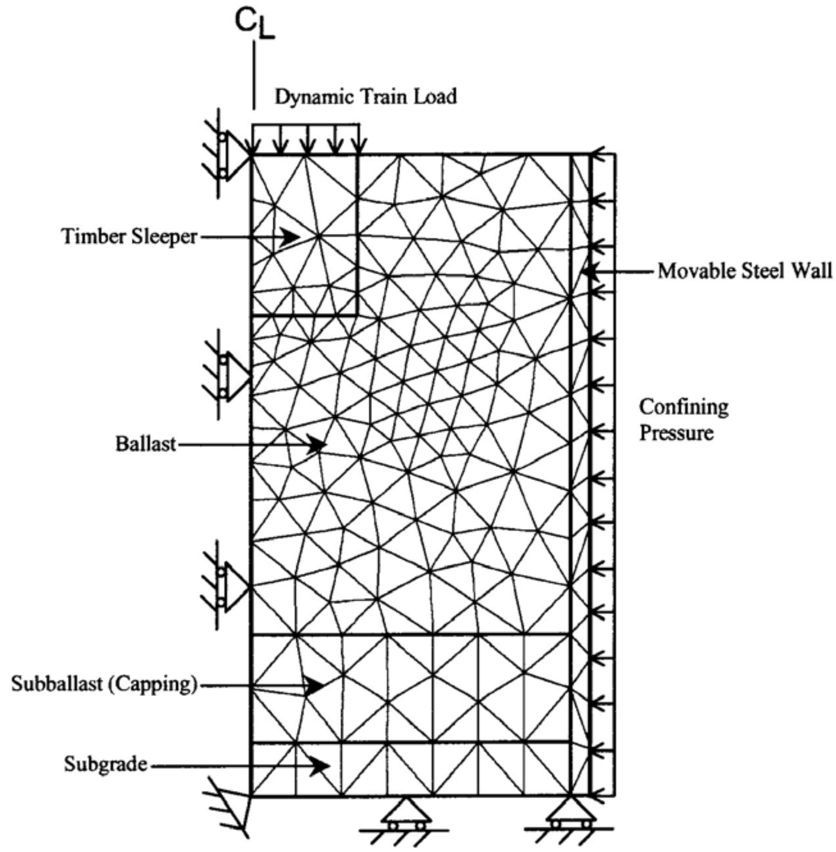


Figure 7 – Finite element mesh used in PLAXIS for the prismoidal triaxial apparatus (Indraratna et al. 2005)

depth of geosynthetics beneath the sleeper is first modeled at 300 mm (i.e. at the ballast capping interface) and then decreased by intervals of 50 mm so that the placement depth of geosynthetics can be tested at 250, 200, 150, and 100 mm, respectively. The results are given in Figure 8. It can be seen that the deformation of recycled ballast is decreased from 13.3 mm to 12.1 mm when the placement depth of geosynthetics beneath the sleeper is reduced from 300 mm to 200 mm. It is also observed that there is almost no improvement in the deformation characteristics of recycled ballast when the placement depth of geosynthetics is decreased from 200 mm to 150 mm, below which the deformation of recycled ballast is increased again to 16.3 mm at 100 mm depth. This demonstrates that there is a threshold depth below which geosynthetics cannot be kept in place under the effect of train wheel load and thus, geosynthetics do not provide the confinement required for ballast to resist settlement. This threshold depth is shown to be between 150 to 200 mm. The results also indicate that the optimum location of geosynthetics for improving the deformation characteristics of recycled ballast may be taken to be 200 mm. It should be noted that, to allow for ballast cleaning in the field, if the required thickness of ballast is more than 200 mm, placement of geosynthetics at the obtained optimum location (i.e. at 200 mm) may not be feasible. Consequently, in such cases, the location of geosynthetics could be used to at the bottom of ballast bed (i.e. at the ballast/capping interface).

Table 6 – Parameters of the rail track materials used in the finite element analysis

Parameter	Ballast		Subballast	Subgrade	Timber sleeper	Steel Wall	Geogrid
	Fresh	Recycled					
Model	HS	HS	MC	Elastic	Elastic	Elastic	Elastic
γ (kN/m³)	15.3	15.3	21.3	17	—	—	—
E_{50}^{ref} (MPa)	150	70	—	—	—	—	—
E_{oed}^{ref} (MPa)	150	70	—	—	—	—	—
E_{ur}^{ref} (MPa)	450	210	—	—	—	—	—
E (MPa)	—	—	100	40	10.55	210000	—
EA (kN/m)	—	—	—	—	—	—	525
v	—	—	0.35	0.4	0.33	0.33	—
v_{ur}	0.2	0.2	—	—	—	—	—
c (kN/m²)	0.0	0.0	0.0	—	—	—	—
φ (degree)	50	45	45	—	—	—	—
Ψ (degree)	0	0	0	—	—	—	—
P_{ref}(kN/m²)	100	100	—	—	—	—	—
m	0.5	0.5	—	—	—	—	—
K_o^{nc}	0.3	0.3	—	—	—	—	—
R_f	0.9	0.9	—	—	—	—	—

HS = Hardening-Soil model, MC = Mohr-Coulomb model, γ = unit weight, E_{50}^{ref} = secant stiffness at 50% strength for loading conditions, E_{ur}^{ref} = triaxial unloading/reloading stiffness, E_{oed}^{ref} = tangent stiffness for primary oedometer loading, EA = elastic normal (axial) stiffness, v = Poisson's ratio for loading conditions, v_{ur} = Poisson's ratio for unloading/reloading conditions, c = effective cohesion, φ = effective friction angle, Ψ = dilatancy angle, P_{ref} = reference confining pressure, m = stress dependent stiffness factor, k_o^{nc} = coefficient of earth pressure at rest for normal consolidation, R_f = failure ratio.

Table 7 – Deformation of ballast at 100 load cycles by test and FEA

Parameter	Wet recycled ballast		Wet recycled ballast stabilized with geogrids at ballast/capping interface	
	Test	FEA	Test	FEA
Settlement (mm)	15.9	15.8	13.4	13.3
Vertical strain (%)	4.3	4.5	3.4	3.8

CONCLUSIONS

The use of three types of geosynthetics (i.e. geogrid, geotextile, and geocomposite) in stabilizing recycled ballast was investigated in the laboratory and by the numerical modeling. A large-scale prismoidal triaxial apparatus that has moveable walls was used in the laboratory model, and the finite element analysis (PLAXIS) was used for the numerical modeling. The laboratory test results indicate that the deformation of railway ballast, both fresh and recycled,

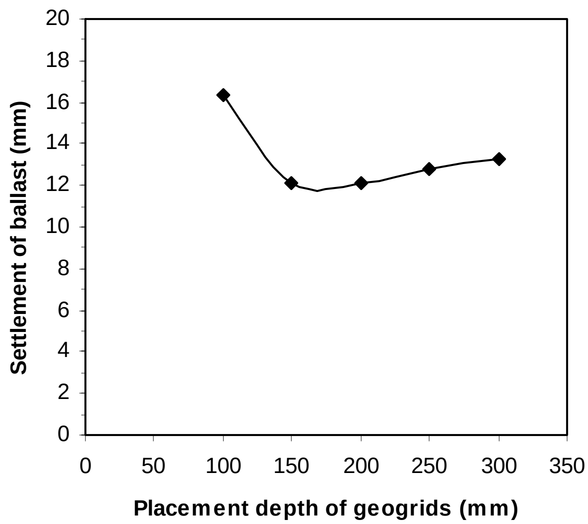


Figure 8 – Optimum location of geosynthetics in rail track substructure by finite elements

increases non-linearly with the number of load cycles. The study confirms that recycled ballast gives higher settlement and particle breakage than fresh ballast under identical loading and boundary conditions. Saturation of recycled ballast also increases its deformation characteristics. In general, it was found that the inclusion of any of the three types of geosynthetics used in this study improves ballast performance and stability. However, the inclusion of geocomposite (i.e. geogrid and non-woven geotextile bonded together) gives significantly better stability to recycled ballast. The vertical settlement of recycled ballast stabilized with geocomposite was decreased to even less than that of fresh ballast (without geosynthetics) and the breakage index was reduced to almost equal to that of fresh ballast, which minimizes the need for ballast replacement during maintenance. In addition, the lateral strain of recycled ballast was decreased to a value less than that of fresh ballast, which decreases the need for crib and shoulder ballast replacement (i.e. the track will benefit from minimum confinement). Geocomposite is very effective in preventing the migration of fines from the underlying capping and subgrade layers, particularly in saturated condition, and therefore, keeps the ballast relatively clean. This has tremendous implications in the maintenance cycle of rail tracks and consequently the cost of track maintenance. The study also indicates that recycled ballast of larger grains of size 30–50 mm is more vulnerable to degradation. Given the proven functions of geocomposite in ballast reinforcement, separation, and drainage (filtration), it is expected that Australian railways will adopt such modernization in the future design of ballasted tracks.

The results of the plane strain finite element numerical modeling indicate that there is a threshold depth below which the geosynthetics cannot be kept in place under the effect of train wheel load and thus, geosynthetics do not provide the required confinement for ballast to resist settlement. This threshold depth was found to be between 150 to 200 mm. The results also indicate that the optimum location of geosynthetics for improving rail track deformation may be taken to be 200 mm beneath the sleeper, considering that a minimum depth of ballast of 150 mm beneath the sleeper has to be left without geosynthetics, to allow for tamping. However, if the design ballast thickness needed is more than 200 mm, it will be convenient to place the geosynthetics at the bottom of the ballast bed (i.e. at the ballast capping interface), to allow for maintenance requirements (e.g. ballast cleaning and tamping).

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